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CRITICAL ANALYSIS OF THE PROGRESSIVE SUBSTITUTION METHOD FOR MATERIAL BUCKLING MEASUREMENTS

by

G. CASINI and J. MÉGIER

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ORGEL Program

Joint Nuclear Research Center
Ispra Establishment - Italy

Reactor Physics Department
Applied Mathematical Physics Service

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G. CASINI AND J. MÉGIER
EURATOM JOINT NUCLEAR RESEARCH CENTRE, ISPRA, ITALY

Abstract — Résumé — Аннотация — Resumen

CRITICAL ANALYSIS OF THE PROGRESSIVE SUBSTITUTION METHOD FOR MATERIAL BUCKLING MEASUREMENTS. A critical analysis of the methods of interpretation for progressive substitution measurements is in progress at the Centre of Ispra (EURATOM). These studies are intended for the interpretation of material buckling measurements to be performed in the ECO (Orgel Critical Experience) reactor starting in 1964.

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ANALYSE CRITIQUE DE LA MÉTHODE DE SUBSTITUTION PROGRESSIVE UTILISÉE POUR MESURER LE LAPLACIEN MATIÈRE. Le Centre d'Ispra (EURATOM) procède actuellement à une analyse critique des méthodes d'interprétation des mesures faites par substitution progressive. Ces études ont pour objet d'interpréter les mesures du laplacien matière, qui seront effectuées dans le réacteur ECO (Expérience Critique Orgel) à partir de 1964.

Le mémoire a trait à la méthode d'interprétation des mesures obtenues par substitution progressive; on applique une théorie à deux groupes à un réacteur avec réflecteur, dont les régions sont supposées être cylindriques et homogénéisées. Parmi les points étudiés figurent:

1. Limites de validité de la méthode lorsque augmentent les écarts entre les propriétés neutroniques du réseau étudié et du réseau de référence.
2. Effets de l'homogénéisation cylindrique en fonction du nombre de barres substituées.
3. Effets des approximations sur les calculs concernant le réflecteur.

КРИТИЧЕСКИЙ АНАЛИЗ МЕТОДА ПОСТЕПЕННОГО ЗАМЕЩЕНИЯ, ПРИМЕНЯЕМОГО ДЛЯ ИЗМЕРЕНИЯ МАТЕРИАЛЬНОГО ЛАПЛАСИАНА. В научно-исследовательском центре в Испре (Евратом) осуществляется критический анализ методов интерпретации результатов измерений, проводимых методом постепенного замещения. Эти исследования направлены на получение интерпретации результатов измерений материального лапласиана, которые должны быть выполнены, начиная с 1964 года, на реакторе ECO (Оргельский критический опытный реактор).

Дается описание метода интерпретации результатов измерений методом постепенного замещения на основании двухгрупповой теории, применяемой к реактору с отражателем, зоны которого, как предполагается, являются цилиндрическими и гомогенизированными. Некоторые из анлизируемых пунктов:

Пределы пригодности метода с возращающими различиями между нейтронными свойствами испытательной и эталонной решеток.

Значение цилиндрической гомогенизации как функции ряда замещаемых стержней.

Значение приближений в расчете отражателя.

ANÁLISIS CRÍTICO DEL MÉTODO DE SUSTITUCIÓN PROGRESIVA PARA MEDICIONES EN LAPLACIANOS MATERIALES. En el Centro de Ispra (EURATOM) se está realizando un análisis crítico de los métodos de interpretación de las mediciones por sustitución progresiva. Su finalidad es evaluar los resultados de la medición de los laplacianos materiales del reactor ECO (Experimento Crítico Orgel), que debe comenzar en 1964.

La memoria trata de un método de interpretación basado en una teoría de dos grupos aplicada a un reactor con reflector cuyas zonas se suponen cilíndricas y homogéneas. Entre otros puntos, analiza los siguientes:

1. Los límites de validez del método cuando aumentan las diferencias entre las propiedades neutrónicas del reticulado que se ensaya y el de referencia.
2. El efecto de la homogeneización cilíndrica en función del número de barras sustituidas.
3. El efecto de las aproximaciones en el cálculo del reflector.

1. INTRODUCTION

A complete series of buckling measurements will be performed in 1964 on ECO (Expérience Critique Orgel), a natural uranium-fuelled, heavy-water-moderated critical assembly now in construction at the EURATOM Joint Nuclear Research Centre at Ispra [1]. First the neutronic characteristics of the pile loaded with the "reference" fuel elements (clusters of 19 rods of uranium metal contained in a double tube filled with organic liquid) will be determined by flux mapping. Then the buckling of variously fuelled lattices will be measured by the progressive substitution technique.

The aim of this report is to illustrate the method established at EURATOM, to interpret the substitution experiments and to discuss the approximations involved in view of defining the range of applicability of the method itself.

2. OUTLINE OF THE METHOD IN USE AT EURATOM

The substitution approach to determine the buckling of a lattice has been used for several years in various laboratories [2, 3, 4]. Methods have been established to interpret the experimental results; particular attention has been reserved to the "progressive" substitution measurements on heavy-water-moderated critical assemblies performed by French and Swedish national centres.

It is foreseen that the same technique will be used in the ECO experimental programme. Therefore a method of interpretation, developed on the basis of the French work [5], has been established and programmed for IBM-7090 (BERTHE code) at the EURATOM Joint Nuclear Research Centre at Ispra.

A two-group, two-homogenized-core region diffusion model has been assumed. Practically no approximation in the analytical development of the theory is made. The effectiveness of the radial graphite reflector and of the aluminium tank between the core and the reflector are directly incorporated in the programme instead of using a reflector coefficient as in the French method [5].

A series of check calculations with a normal two-group diffusion code (WANDA and RIFIFI codes [6, 7]) have been found to be satisfactory. In the appendix the main lines of the developed method are indicated.

In particular the formalism which takes into account the aluminium tank has been found to be necessary. To study this point two BERTHE calculations have been performed for a typical series of ECO substitution experiments. The buckling of the reference lattice was 4.346 m^{-2}. The difference

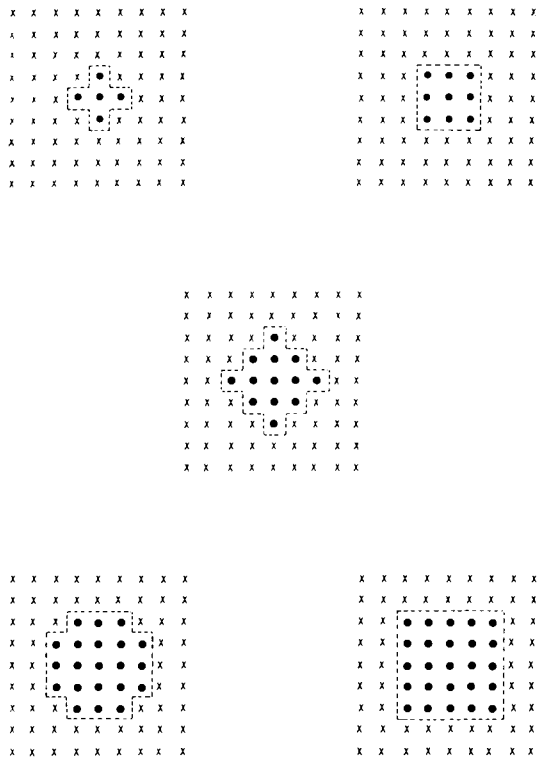


Fig. 1

ECO substitutions

between the test and reference lattice was $-0.905\ m^{-2}$. The series of substitutions is given in Fig. 1. The corresponding heavy-water level variations (ΔH_i) as calculated by RIFIFI are listed in Table I.

In the first BERTHE calculation a value of q_t (see appendix) of 0.012 (corresponding to an aluminium thickness of 1 cm) was assumed. In the second one the tank effect was not included ($q_t = 0$). A difference of $0.20\ m^{-2}$ in ΔB^2 was found: this shows the importance of being able to evaluate the influence of the thin aluminium layer between core and reflector for such type of calculations.

3. INPUT DATA INFLUENCE

Table II shows the influences on the buckling difference between test and reference region (ΔB^2) caused by small variations in the input nuclear data of the test region and in the measured heavy-water levels during the replacements (ΔH_i). The influence of the diffusion coefficients seems to be fairly important. However the uncertainty of these parameters for the test lattice as compared with that for the reference region is certainly less than 5%. Therefore an error inferior to $0.02\ m^{-2}$ can be expected for this effect.

TABLE I

HEAVY-WATER LEVEL VARIATIONS FOR SUBSTITUTION EXPERIMENTS

No. of substituted rods	Radius of substituted zone (cm)	ΔH_i (cm)
5	26.49	2.25
9	35.54	4.11
13	42.72	5.93
21	54.29	9.49
25	59.24	11.21

TABLE II

INFLUENCE OF INPUT DATA ON BUCKLING DIFFERENCE BETWEEN TEST AND REFERENCE REGION

Parameter symbol*	Numerical value	Parameter variation	Variation on ΔB^2 (m^{-2})
D_{1r}	1.257	+ 5%	- 0.0234
D_{1t}	0.819	+ 5%	- 0.0263
L_1^2	85.88	+ 5%	- 0.0002
τ_1	106.36	+ 5%	- 0.0001
p_1	0.8717	+ 2%	0.0
H_i	-	+ 0.1 cm	+0.0150

* D : Diffusion coefficient
L^2: Diffusion area
τ : Slowing-down area
p : Resonance escape probability.

Subscript 1: Test region.
Subscript r: "Fast group".
Subscript t: "Thermal group".

As far as the error in level is concerned, the accuracy in the ECO level measurement being 0.2 mm, the influence on ΔB^2 could be reduced to less than 0.005 m^{-2}.

4. APPROXIMATIONS INVOLVED IN THE METHOD

As we said, the scheme used to determine from experimental values of the critical level the buckling of the test lattice involves a certain number of approximations. In the following chapters we will try to evaluate the errors which can be expected in the ECO operation cases mentioned in the introduction.

The main effects to be treated are: (a) the cylindrical-shape approximation in the test region and (b) the heterogeneity effects.

(a) Cylindrical-shape approximation in the test region

In BERTHE the test region is considered to be cylindrical. The radius of the region is calculated as:

$$R_i = d(N_i/\pi)^{1/2},$$

where:

N_i = number of substituted rods and

d = pitch of the lattice.

The choice of this radius is somewhat arbitrary because in the boundary region between the two zones it is not possible to define an equivalent cell for each rod. To examine the cause of this uncertainty we have compared the normal BERTHE results with those obtained by increasing the radii of the different substituted regions by a fixed amount. Table III gives the results for $\Delta R_i = +2$ cm.

TABLE III

COMPARISON OF THE NORMAL BERTHE RESULTS WITH THOSE OBTAINED BY INCREASING RADII

No. of substituted rods	ΔB^2 (m^{-2})	$\delta(\Delta B^2)$ (m^{-2})
5	-0.507	-0.0022
9	-0.905	-0.0054
13	-1.284	-0.0120
21	-1.528	-0.003
25	-1.702	-0.005

The calculations have been performed for the ECO pile geometry; a pitch of 22.6 cm and five substitutions (5, 9, 13, 21, 25 elements replaced) have been considered. As can be seen, the effect remains in all cases relatively small.

The influence of the form of the boundary line has also been studied by comparing for the ECO substituted configurations the results of a one-dimensional and a two-dimensional calculation.

In the first calculation (WANDA programme) the pile has been schematized as in BERTHE: three cylindrical regions (test region, reference region and radial reflector) have been considered. The radius of the test region varied according to the number of fuel elements substituted.

For each pile configuration a critical extrapolated height was obtained; this value (together with the nuclear data used in WANDA) was introduced as input data into a two-dimensional calculation (EQUIPOISE programme [8]). In this second case the boundary limit between the two-core regions was determined according to the cell hypothesis as indicated, for the different substitutions, in Fig. 1.

The EQUIPOISE results (based on the critical heights obtained by WANDA) are shown in Table IV; they are expressed as k_{eff} variations (in

TABLE IV

EQUIPOISE RESULTS

Pitch (cm)	ΔB^2 (m^{-2})	$\delta k/k$ (pcm)				
		5	9	13	21	25
18.8	-2.36	+ 1.0	+ 1.0	+ 0.0	+ 0.0	-0.1
22.3	-1.48	+ 0.0	+ 1.0	- 2.0	+ 1.0	-3.0
26.6	-0.97	+ 0.0	+ 1.0	- 5.0	+ 0.0	-6.0

pcm = 10^{-5}) from the critical conditions. These figures give a direct indication of the error involved in the cylindrical-shape approximation for the boundary line. Taking into account that in ECO 1 pcm of reactivity corresponds to about 0.2 mm variation in the critical level and comparing with the data of Table II (1 mm in ΔH_i means a variation of 0.0156 in ΔB^2), it can be concluded that this effect is relatively small, even though it is slightly more pronounced in the configurations with 13 and 25 rods which are farthest away from the circular shape.

A general conclusion can be derived from these results: apart from the heterogeneity effects of the lattices (which will be studied in the following sections), the form (and thus the number of rods) of the region does not seem to play an important part in the substitution technique.

In this perspective the WANDA-EQUIPOISE comparison has been extended to the case of 17 replaced rods (Fig. 2) where the central zone configuration is less symmetrical. The results are given in Table V.

The error introduced by the cylindrical-shape approximation remains fairly small. This means that such a substitution could be introduced in the replacement operations to increase the number of experimental data or to eliminate, if the heterogeneity effects are not too important, the 25-rod replacement.

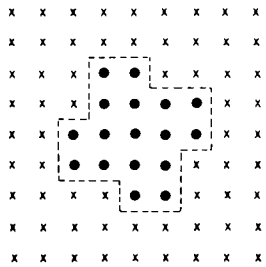


Fig. 2

17-rod substitution

TABLE V

EXTENSION OF THE WANDA-EQUIPOISE COMPARISON

Pitch, (cm)	ΔB^2 (m^{-2})	$\delta k/k$ (pcm)
18.8	-2.36	+10.0
21.0	-0.905	- 7.0

(b) Heterogeneity effects

As previously said, in the BERTHE method the test and reference regions are homogenized; this means that the heterogeneity effects of the lattices are supposed to be independent from the dimensions of the regions.

However, for under-moderated lattices this hypothesis is not justified. This fact prompted us to study the limits of validity of such an assumption in the ECO substitution measurements.

The analysis is not concerned with fuel elements containing void where the anisotropy of the neutron streaming is important. The main effects to be considered then are: (i) resonance absorption and (ii) thermal absorption.

Indeed for the pitches which will be considered in the ECO reactor (> 18.0 cm) only a quite small fraction of U^{238} fissions in a fuel element are produced by neutrons coming from other rods. Thus the heterogeneity fast effects can be neglected.

The resonance absorption effect can be illustrated in the following manner: let us consider an infinite heterogeneous lattice. The resonance absorption in a rod can be considered as the sum of the absorption of neutrons born in the rod itself plus the absorption of neutrons born in the surrounding rods. All these absorptions do not depend on the intensity of the fission source because the lattice is infinitely extended. However if we have two connected lattices, as in the case of substitution experiments, some rods of one lattice are surrounded also by rods of the other lattice. If the

uranium section per channel is quite different for the two lattices the fast source will also be different and the absorption for the boundary rods will be different from that of an infinite lattice.

Analytically, if p_∞ indicates the resonance escape probability for rod 0 in an infinite moderator sea and p_0 the same in the lattice, the resonance absorption can be written

$$a = \frac{1-p_0}{1-p_\infty} = \sum_{j=0}^{\infty} \frac{S_j}{S_0} e^{-r_j/4\tau_R}, \qquad (1)$$

where:

τ_R = slowing-down area to the resonance energy

r_j = distance from rod 0 to the rod j of the lattice

S_j = intensity of the fast source of rod j.

For the sake of simplicity in formula (1) a line source has been assumed to calculate, on the basis of the Fermi-age model, the slowing-down distribution of the neutrons. Furthermore the resonance absorption has been assumed to occur only at a certain energy level (single-energy approximation).

In the case of an infinite lattice Eq. (1) becomes

$$a = \sum_{j=0}^{\infty} e^{-r_j/4\tau_R}. \qquad (2)$$

The correction introduced by the presence of the other type of rods can be written in the following form:

$$\frac{\Delta a}{a} = \frac{\Delta(1-p_0)}{1-p_0} = 1 - \frac{\sum_{j=0}^{\infty} (S_j/S_0) e^{-r_j/4\tau_R}}{\sum_{j=0}^{\infty} e^{-r_j/4\tau_R}}. \qquad (3)$$

In practice the calculation has been done as follows: let us consider the pile configuration of Fig. 3(a). For each rod of the test and reference lattice $\Delta a/a$ according to Eq. (3) has been evaluated. Then the core has been divided into five regions as indicated in Fig. 3(b). The resonance absorption of each of these regions has been calculated by correcting the p-values (for the infinite lattice) according to the $\Delta a/a$ already determined. On the basis of these data a WANDA calculation has been performed; the critical height so obtained has been compared to the value corresponding to the normal two-region-core model used in BERTHE.

The results for an ECO case are shown in Table VI. The data are the following:

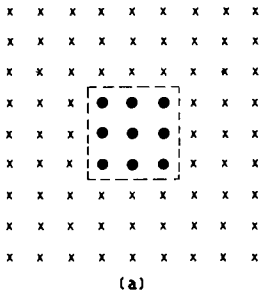
Pitch: 18.8 cm

τ_R : 55.0 cm^2

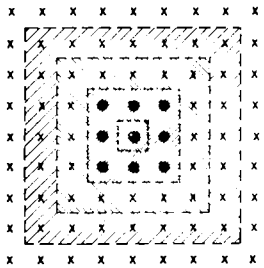
Fission-source ratio between test and reference lattices: 0.67

$B^2_{Ref.}$: 4.076 m^{-2}

ΔB^2 : -1.394 m^{-2}



(a)



(b)

Fig. 3

9-rod substitution

TABLE VI

RESULTS FOR AN ECO CASE

No. of substitutions	ΔH (cm)	ΔH' (cm)	ΔH - ΔH'
5	2.02	2.13	-0.11
9	4.66	4.67	-0.01
13	6.06	6.10	-0.04
21	10.35	10.53	-0.18
25	13.33	13.41	-0.08

ΔH are the variations of the critical level according to the different substitutions, as calculated by WANDA for the two-region-core configuration. ΔH' are the corresponding results from the many-region calculations (5 in the case of the substitution 9). On the basis of the two series of ΔH so obtained, two BERTHE calculations have been performed : the results showed a difference of only 0.004 m^{-2} in ΔB^2.

In the calculation the sources have been assumed to be linear. In fact in the practical case here considered the fuel elements have a diameter of about 7.0 cm. If the distance between two rods r_j in the $\Delta a/a$ calculation is considered to be the distance between the boundaries of two fuel channels, the resonance absorption effect increases fairly sensibly. A second calculation based on this hypothesis has been done and the results are given in Table VII. The corresponding ΔB^2 variation is 0.024 m^{-2}. Therefore it

TABLE VII

RESULTS OF A SECOND CALCULATION

No. of substitutions	ΔH (cm)	$\Delta H'$ (cm)	$\Delta H - \Delta H'$
5	2.02	2.23	-0.21
9	4.66	4.71	-0.05
13	6.06	6.06	0.0
21	10.35	10.69	-0.34
25	13.33	13.46	-0.13

seems that, at least for the ECO pile configurations, this effect does not become too important, also for the most under-moderated lattices.

Two main thermal absorption effects can be envisaged: (a) a spatial effect and (b) a spectrum effect.

Point (a) may be considered analogous to the resonance absorption effect and treated similarly. Specifically the neutron flux distribution across the cell is supposed to be the same as for an infinite lattice; near the boundary between the two-core zones this condition is not verified. The corresponding effect on the criticality can be easily evaluated by comparing the results of a homogenized two-region calculation (as in BERTHE) with a heterogeneous calculation (of the Feinberg-Galanin type) where the difficulties connected with the superposition of the microscopic and macroscopic flux distribution are automatically by-passed.

This effect has already been studied in Saclay and it has been found to be fairly small for some of the heavy-water lattices tested in Aquilon II [9]. Similar calculations to check the validity of this hypothesis for ECO experiments are now in progress at EURATOM.

Point (b) is connected with the fact that in the boundary region the thermal spectrum will be intermediate between those which would correspond to the two infinite lattices of the test and reference region.

This effect could be sensible if the uranium sections per cell of the test and reference regions (i.e. the moderating ratios, because the pitch is the same in all the pile) are sensibly different. To check this point we proceeded in the following manner. It was assumed that in the boundary region (constituted by two rings of test and reference rods respectively) the thermal

spectrum averaged cross-sections of the fuel were the half-sums of the values corresponding to the two infinite lattices.

On the basis of this data a four-region-core WANDA calculation has been compared with a normal two-region calculation. The results are indicated in Table VIII.

TABLE VIII

COMPARISON OF A FOUR-REGION CORE WANDA CALCULATION WITH A NORMAL TWO-REGION CALCULATION

No. of substituted rods	ΔH (cm)	$\Delta H'$ (cm)	$\Delta H - \Delta H'$
9	2.65	2.62	0.03
25	7.32	7.19	0.13

To calculate the spectrum-averaged cross-sections the French method [10] has been used. The two lattices were constituted of single rods of 2.5 and 1.75 cm radius directly immersed in heavy water. The Horowitz and Tretiakoff parameters for the two lattices were:

Moderator temperature: $T_m = 293°K$,
Epithermal factor: $r = 0.0046$ and 0.010 and
Heterogeneity factor: $z = 1.5$ and 2.0.

As can be seen, the moderating conditions of the two lattices are very different. The ΔB^2 variation caused by the spectrum effects is 0.029 m^{-2}; by taking into account that this is a rather extreme case, we can conclude that for natural uranium lattices the effect on spectrum of lattice heterogeneities is generally rather small. This probably would not be true for fuels containing plutonium where the condition of a similar epithermal factor in test and reference region is more stringent [11].

5. CONCLUSIONS

The preceding theoretical analysis gives some confidence in the use of the BERTHE method to interpret the progressive substitution measurements in the ECO reactor. In particular the hypothesis of cylindrical shape for the test region seems to be fairly justified. In these conditions the extension of the substitution configurations to less symmetrical cases could be envisaged. Some caution must however be exercised as far as the moderating conditions for reference and test lattice are concerned. If such conditions are sensibly different from one another the heterogeneity effects cannot be disregarded. In particular, the 5-rod substitution could be difficult to interpret.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to Professor A. Kind for his continuous support and useful criticism. They are grateful to Messrs. R. Naudet and M. Chabrillac of the Commissariat à l'énergie atomique (Saclay) for most helpful discussions and for supplying the results of comparison calculations.

Finally they would like to thank Mr. C. Daolio who programmed the BERTHE code and Mr. S. Stramaccia who has performed the work of preparing the data for computer calculations.

APPENDIX

I. SURVEY OF THE REFLECTOR CALCULATION WITHOUT THIN LAYER

1.1 In the case of a two-region bare reactor the critical equation for the core can be written as follows [12]:

$$U + VS = 1,$$

with

$$U = \left(\frac{J_0}{Y_0}\right)_{\mu_2 R_e} \left(\frac{Y_0 - \mu_2 \Lambda Y_1}{J_0 - \mu_2 \Lambda J_1}\right)_{\mu_2 R_0}$$

$$V = \left(\frac{K_0 - (t_1/t_4)\nu_2 \Lambda K_1}{K_0 - (t_3/t_2)\nu_2 \Lambda' K_1}\right)_{\nu_2 R_0} \left[\left(\frac{J_0 - \mu_2 \Lambda' J_1}{J_0 - \mu_2 \Lambda J_1}\right)_{\mu_2 R_0} - \left(\frac{J_0}{Y_0}\right)_{\mu_2 R_e} \left(\frac{Y_0 - \mu_2 \Lambda' Y_1}{J_0 - \mu_2 \Lambda J_1}\right)_{\mu_2 R_0}\right]$$

$$S = \frac{(T_1 - T_2)(S_1 - S_2)}{(T_1 - S_2)(S_1 - T_2)},$$

where: J_0, J_1, Y_1, K_0, K_1: Bessel functions

μ_2^2: positive radial buckling of the reference lattice

$-\nu_2^2$: negative radial buckling of the reference lattice

μ_1^2: positive radial buckling of the test lattice

$-\nu_1^2$: negative radial buckling of the test lattice

$$\Lambda = \frac{1}{t_1 \mu_1} \left(\frac{J_0}{J_1}\right)_{\mu_1 R_0} \qquad \Lambda' = -\frac{1}{t_3 \nu_1} \left(\frac{I_0}{I_1}\right)_{\nu_1 R_0}$$

t_1, t_2, t_3, t_4: terms including the ratios between the diffusion coefficients of the test and reference lattices

R_0: central test zone radius

R_e: core extrapolated radius.

S_1, T_1: Coupling coefficients between fast and thermal fluxes in the homogenized test zone.

S_2, T_2: Coupling coefficients between fast and thermal fluxes in the homogenized reference zone.

The fast and thermal fluxes in the reference zone are linear combinations of the functions $J_0(\mu_2 r) + \epsilon Y_0(\mu_2 r)$ and $I_0(\nu_2 r) + \epsilon' K_0(\nu_2 r)$ where ϵ and ϵ' are constant numbers. The critical condition leads to the value $-(J_0/Y_0)_{\mu_2 R_e}$ for ϵ.

1.2. In the case of a reactor with lateral reflector the expressions U and V are unchanged except that the value given to ϵ by the critical condition is no longer $-(J_0/Y_0)_{\mu_2 R_e}$.

We just outline here the calculations, first established by JONSSON in a private communication [12]. The boundary conditions at the interface between core and reflector can be written, if we suppose the same fast and thermal diffusion coefficient in the reference zone and the reflector.
For the fluxes

$$\begin{pmatrix} \phi_{2r} \\ \phi_{2t} \end{pmatrix}_{R_1} = \begin{pmatrix} \phi_{3r} \\ \phi_{3t} \end{pmatrix}_{R_1}$$

with

$$\begin{pmatrix} \phi_{2r} \\ \phi_{2t} \end{pmatrix}_{R_1} = a_2 \begin{pmatrix} 1 & m_2 \\ S_2 & m_2 T_2 \end{pmatrix} \begin{pmatrix} X_2 \\ Y_2 \end{pmatrix}_{R_1} = M_2 \begin{pmatrix} X_2 \\ Y_2 \end{pmatrix}_{R_1}$$

$$\begin{pmatrix} \phi_{3r} \\ \phi_{3t} \end{pmatrix}_{R_1} = a_3 \begin{pmatrix} 1 & 0 \\ S_3 & m_3 \end{pmatrix} \begin{pmatrix} X_3 \\ Y_3 \end{pmatrix}_{R_1} = M_3 \begin{pmatrix} X_3 \\ Y_3 \end{pmatrix}_{R_1} \qquad (1)$$

so that

$$\begin{pmatrix} X_2 \\ Y_2 \end{pmatrix}_{R_1} = M_2^{-1} \; M_3 \begin{pmatrix} X_3 \\ Y_3 \end{pmatrix}_{R_1} .$$

For the currents

$$\begin{pmatrix} X'_2 \\ Y'_2 \end{pmatrix}_{R_1} = M_2^{-1} \; M_3 \begin{pmatrix} X'_3 \\ Y'_3 \end{pmatrix}_{R_1} , \qquad (2)$$

where the subscripts mean: r: fast group; t: thermal group; 2: reference zone; 3 reflector (1 would be the test zone); R_1 indicates that the functions are calculated at the interface between core and reflector, the radius of which is R_1.

and where:

$X_2 = J_0(\mu_{2r}) + \epsilon Y_0(\mu_{2r})$

$Y_2 = I_0(\nu_{2r}) + \epsilon' K_0(\nu_{2r})$

$X_3 = I_0(\mu_{3r}) - (I_0/K_0)_{\mu_3 R_2} \cdot K_0(\mu_{3r}) = Z_0(\mu_{3r})$

$Y_3 = Z_0(\nu_{3r})$

R_2: outer reflector radius, including the extrapolation distance.

S_2, T_2, S_3: coupling coefficients between fast and thermal fluxes.

Equations (1) and (2) can be expressed with the single condition:

$$\begin{pmatrix} X_2 + \lambda X'_2 \\ Y_2 + \lambda Y'_2 \end{pmatrix}_{R_1} = M_2^{-1} \; M_3 \begin{pmatrix} X_3 + \lambda X'_3 \\ Y_3 + \lambda Y'_3 \end{pmatrix}_{R_1}$$

(where λ is an arbitrary parameter)

which leads to the two equations

$$(X_2 + KX'_2)_{R_1} + m_2(Y_2 + KY'_2)_{R_1} = 0 \tag{3}$$

and

$$(X_2 + \eta X'_2)_{R_1} + m_2\frac{T_2}{S_2}(Y_2 + \xi Y'_2)_{R_1} = 0 \tag{4}$$

or:

$$(J_0K) + \epsilon(Y_0K) + m_2(I_0K) + m_2\epsilon'(K_0K) = 0 \tag{3'}$$

and

$$(J_0\eta) + \epsilon(Y_0\eta) + m_2\frac{T_2}{S_2}(I_0\xi) + m_2\frac{T_2}{S_2}\epsilon'(K_0\xi) = 0, \tag{4'}$$

where K is such that $X_3 + KX'_3 = 0 : \lambda = K = -(Z_0/Z'_0)_{\mu_3 R_1}$

K' is such that $Y_3 + K'Y'_3 = 0 : \lambda = K' = -(Z_0/Z'_0)_{\nu_3 R_1}$

and:

$$\eta = K' + (K - K')\frac{S_3}{S_2}, \qquad \xi = K' + (K - K')\frac{S_3}{T_2}.$$

$$(J_0K) = J_0(\mu_2 R_1) - \mu_2 K J_1(\mu_2 R_1), \qquad (Y_0K) = Y_0(\mu_2 R_1) - \mu_2 K Y_1(\mu_2 R_1), \tag{5}$$

etc.

Eliminating m_2 between (3') and (4') and noting that $\epsilon'(K_0K)_{R_1} \ll (I_0K)_{R_1}$ and that $\epsilon'(K_0\xi)_{R_1} \ll (I_0\xi)_{R_1}$ one finds the new value of ϵ:

$$\epsilon = -\left(\frac{J_0 - \mu_2\Lambda_1 J_1}{Y_0 - \mu_2\Lambda_1 J_1}\right)_{\mu_2 R_1}. \tag{6}$$

where Λ_1 means the expression $\Lambda_1 = \frac{1}{\mu_2}\left(\frac{J_0 + \epsilon Y_0}{J_1 + \epsilon Y_1}\right)_{\mu_2 R_1}$. Equations (3) and (4) give for this expression the value

$$\Lambda_1 = \frac{\eta(I_0K) - (T_2/S_2)K(I_0\xi)}{(I_0K) - (T_2/S_2)(I_0\xi)}. \tag{7}$$

Substituting the value of ϵ in (6) for $-(J_0/Y_0)_{\mu_2 R_e}$ in 1.1, one obtains the expression for U and V in the case of a reactor with lateral reflector.

II. DIFFUSION-COEFFICIENTS CORRECTION AND THIN LAYER FORMALISM

These extensions will lead to a more general formulation of Λ_1 and, once more, to a new value of ϵ to be substituted in the former expressions of U and V.

2.1. The boundary conditions, in the case where there is a thin weak absorber layer between reference zone and reflector, and when one takes into account the difference between the diffusion coefficients of these two zones, can be expressed in the following way:

The neutronic currents at (R_{1-}) and (R_{1+}), (R_{1-}) and (R_{1+}) being respectively the inner and outer radii of the thin layer located at the radius R_1 ($R_{1-} = R_1 - (d/2)$; $R_{1+} = R_1 + (d/2)$; d: thin layer thickness), can be written to a very good approximation

$$j^+_{(R_{1+})} = j^+_{(R_{1-})} e^{-q} \simeq j^+_{(R_{1-})}(1-q) \tag{8}$$

$$j^-_{(R_{1-})} = j^-_{(R_{1+})} e^{-q} \simeq j^-_{(R_{1+})}(1-q), \tag{9}$$

where $q = \Sigma_a d$ (Σ_a absorption cross-section of the thin layer material; j^+: outward current; and j^-: inward current).

Let us consider now, in diffusion theory, the expressions of the currents at the boundaries (R_{1-}) and (R_{1+}) of the two-region reference lattice (region 2) and reflector (region 3).

$$j^+_{(R_{1+})} = \frac{\phi_3}{4} - \frac{D_3}{2}\frac{d\phi_3}{dr} \qquad j^+_{(R_{1-})} = \frac{\phi_2}{4} - \frac{D_2}{2}\frac{d\phi_2}{dr}$$

ϕ_3: flux in reflector at (R_{1+}) — D_3: reflector diffusion coefficient
ϕ_2: flux in reference region at (R_{1-}) — D_2: reference region diffusion coefficient

and similar expressions for $j^-(R_{1+})$ and $j^-(R_{1-})$.

Considering these current expressions and the absorption law, (8) and (9), and neglecting the thickness of the layer, i.e. supposing that the changes in current and flux produced by the layer take place discontinuously at the boundary R_1, one finds the following boundary conditions at R_1:

$$\phi_3 = \phi_2 + 2q D_2 \phi'_2 \tag{10}$$

$$\phi'_3 = \frac{q}{2D_3}\phi_2 + \frac{D_2}{D_3}\phi'_2 \tag{11}$$

2.2. In our case, with two groups of neutrons and matrix formalism the boundary conditions can be written

$$\begin{pmatrix} \phi_{3r} \\ \phi_{3t} \end{pmatrix}_{R_1} = \begin{pmatrix} \phi_{2r} \\ \phi_{2t} \end{pmatrix}_{R_1} + \begin{pmatrix} 2q_r D_{2r} & 0 \\ 0 & 2q_t D_{2t} \end{pmatrix} \begin{pmatrix} \phi'_{2r} \\ \phi'_{2t} \end{pmatrix}_{R_1} \tag{10'}$$

$$\begin{pmatrix} \phi'_{3r} \\ \phi'_{3t} \end{pmatrix}_{R_1} = \begin{pmatrix} \frac{q_r}{2D_{3r}} & 0 \\ 0 & \frac{q_t}{2D_{3t}} \end{pmatrix} \begin{pmatrix} \phi_{2r} \\ \phi_{2t} \end{pmatrix}_{R_1} + \begin{pmatrix} \frac{D_{2r}}{D_{3r}} & 0 \\ 0 & \frac{D_{2t}}{D_{3t}} \end{pmatrix} \begin{pmatrix} \phi'_{2r} \\ \phi'_{2t} \end{pmatrix}_{R_1} \tag{11'}$$

where $q_r = \Sigma a_r d$ (fast group)
$q_t = \Sigma a_t d$ (thermal group)

Remembering (cf. 1.2) that $\begin{pmatrix} \phi_{2r} \\ \phi_{2t} \end{pmatrix} = M_2 \begin{pmatrix} X_2 \\ Y_2 \end{pmatrix}$; $\begin{pmatrix} \phi_{3r} \\ \phi_{3t} \end{pmatrix} = M_3 \begin{pmatrix} X_3 \\ Y_3 \end{pmatrix}$

and the same relationships for the flux derivatives, we can again condense (10') and (11') into a single equation

$$M_2^{-1} M_3 \begin{pmatrix} X_3 + \lambda X_3' \\ Y_3 + \lambda Y_3' \end{pmatrix}_{R_1} = \begin{pmatrix} X_2 \\ Y_2 \end{pmatrix}_{R_1} + \left(M_2, \frac{q}{2D_3} \right) \lambda \begin{pmatrix} X_2 \\ Y_2 \end{pmatrix}_{R_1} + \left[\left(M_2, 2qD_2 \right) + \lambda \left(M_2, \frac{D_2}{D_3} \right) \right] \begin{pmatrix} X_2' \\ Y_2' \end{pmatrix}_{R_1},$$

where:

$$\left(M_2, \frac{q}{2D_3} \right) = M_2^{-1} \begin{pmatrix} \frac{q_r}{2D_{3r}} & 0 \\ 0 & \frac{q_t}{2D_{3t}} \end{pmatrix} M_2$$

$$\left(M_2, 2qD_2 \right) = M_2^{-1} \begin{pmatrix} 2q_r D_{2r} & 0 \\ 0 & 2q_t D_{2t} \end{pmatrix} M_2$$

$$\left(M_2, \frac{D_2}{D_3} \right) = M_2^{-1} \begin{pmatrix} \frac{D_{2r}}{D_{3r}} & 0 \\ 0 & \frac{D_{2t}}{D_{3t}} \end{pmatrix} M_2$$

Setting $q_r = q_t = 0$ leads to the simple diffusion coefficient correction, while setting $q_r = q_t = 0$ and $D_2 = D_3$ leads to the formalism used in 1.2.
One finds again two expressions similar to (3) and (4):

$$X_{2R_1} \left(1 + K \frac{q_r}{2D_{3r}} \right) + X_{2R_1}' \left(K \frac{D_{2r}}{D_{3r}} + 2q_r D_{2r} \right) + m_2 \left[Y_{2R_1} \left(1 + K \frac{q_r}{2D_{3r}} \right) + Y_{2R_1}' \left(K \frac{D_{2r}}{D_{3r}} + 2q_r D_{2r} \right) \right] = 0 \quad (12)$$

$$X_{2R_1} \left[1 + K' \frac{q_t}{2D_{3t}} + (K - K') \frac{S_3}{S_2} \frac{q_r}{2D_{3r}} \right] + X_{2R_1}' \left[K' \frac{D_{2t}}{D_{3t}} + (K - K') \frac{S_3}{S_2} \frac{D_{2r}}{D_{3t}} + 2q_t D_{2t} \right]$$

I II

$$+ m_2 \frac{T_2}{S_2}\left\{Y_{2R_1}\left[1+K'\frac{q_t}{2D_{3t}}+(K-K')\frac{S_3}{T_2}\frac{q_r}{2D_{3r}}\right] + Y'_{2R_1}\left[K'\frac{D_{2t}}{D_{3t}}+(K-K')\frac{S_3}{T_2}\frac{D_{2r}}{D_{3r}}+2q_t D_{2t}\right]\right\} = 0 \quad (13)$$

III IV

(12) and (13) can be written like (3') and (4'):

$$[J_0K] + \epsilon[Y_0K] + m_2[I_0K] + m_2\epsilon'[K_0K] = 0 \quad (12')$$

$$[J_0\eta] + \epsilon[Y_0\eta] + m_2\frac{T_2}{S_2}[I_0\xi] + m_2\frac{T_2}{S_2}\epsilon'[K_0\xi] = 0, \quad (13')$$

where:

$$[J_0K] = J_{0(\mu_2R_1)}\left(1+K\frac{q_r}{2D_{3r}}\right) - \mu_2\left(K\frac{D_{2r}}{D_{3r}}+2q_rD_{2r}\right)J_{1(\mu_2R_1)}$$

$$[I_0K] = I_{0(\nu_2R_1)}\left(1+K\frac{q_r}{2D_{3r}}\right) + \nu_2\left(K\frac{D_{2r}}{D_{3r}}+2q_rD_{2r}\right)I_{1(\nu_2R_1)}$$

and similar expressions for $[Y_0K]$ and $[K_0K]$
and where

$$[J_0\eta] = J_{0(\mu_2R_1)}[I] - \mu_2[II]\,J_{1(\mu_2R_1)}$$

$$[I_0\xi] = I_{0(\nu_2R_1)}[III] + \nu_2[IV]\,I_{2(\nu_2R_1)}$$

and similar expressions for $[Y_0\eta]$ and $[K_0\xi]$

Again, eliminating m_2 between (12') and (13') we find the same formalism for the expression of ϵ:

$$\epsilon = -\left(\frac{J_0-\mu_2\Lambda_1J_1}{Y_0-\mu_2\Lambda_1Y_1}\right)_{\mu_2R_1}$$

as given by (6) but Λ_1 is now given by:

$$\Lambda_1 = \frac{\eta^*[I_0K] - \frac{T_2}{S_2}(KD)[I_0\xi]}{[1+(\eta q)][I_0K] - \frac{T_2}{S_2}[1+(Kq)][I_0\xi]},$$

where

$$\eta^* = [II] = K' \frac{D_{2t}}{D_{3t}} + (K - K') \frac{S_3}{S_2} \frac{D_{2r}}{D_{3r}} + 2q_t D_{2t}$$

$$(KD) = K \frac{D_{2r}}{D_{3r}} + 2q_r D_{2r}$$

$$1 + (\eta q) = [I] = 1 + K' \frac{q_t}{2D_{3t}} + (K - K') \frac{S_3}{S_2} \frac{q_r}{2D_{3r}}$$

$$1 + (Kq) = 1 + K \frac{q_r}{2D_{3r}} .$$

It is therefore easy to see that the successive extensions of the method to include the eventualities of lateral reflector, non-equal diffusion coefficients in reflector and reference region, and a thin weak absorber layer between core and reflector affect only the term ϵ in the expressions U and V which can be written under the general form

$$U = -\epsilon \left(\frac{Y_0 - \mu_2 \Lambda Y_1}{J_0 - \mu_2 \Lambda J_1} \right)_{\mu_2 R_0}$$

$$V = \left(\frac{K_0 - (t_1/t_4)\nu_2 \Lambda K_1}{K_0 - (t_3/t_2)\nu_2 \Lambda' K_1} \right)_{\nu_2 R_0} \left[\left(\frac{J_0 - \mu_2 \Lambda' J_1}{J_0 - \mu_2 \Lambda J_1} \right)_{\mu_2 R_0} + \epsilon \left(\frac{Y_0 - \mu_2 \Lambda' Y_1}{J_0 - \mu_2 \Lambda J_1} \right)_{\mu_2 R_0} \right] .$$

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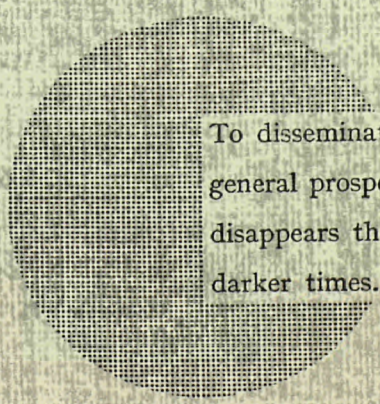
DISCUSSION

R. PERSSON: The errors caused by the cylindrical-shape approximation and by heterogeneity are no doubt related to the perturbance of the reactor during the measurement. If that is so, the error of the buckling in the test region is larger.

G. CASINI: To pass from the $\Delta k/k$ values to ΔB^2 variation, one must first establish the ΔH variation and then calculate the ΔB^2 variation on the basis of the data of Table II of the paper (1 mm corresponds to about 0.015 m^{-2} in ΔB^2).

U. FARINELLI (Chairman): I might perhaps comment that we did similar calculations in connection with substitution experiments in the ROSPO reactor and got very similar results.



To disseminate knowledge is to disseminate prosperity — I mean general prosperity and not individual riches — and with prosperity disappears the greater part of the evil which is our heritage from darker times.

Alfred Nobel